True random coded photon counting Lidar

Bo Liu[1,2,3]*, Yang Yu[1,2], Zhen Chen[1,3] and Weiqiang Han [1,3]

A true random coded photon counting Lidar system is proposed in this paper, in which a single photon detector acts as the true random sequence signal generator instead of the traditional function generator. Compared with the traditional pseudo-random coded method, the true random coded method not only improves the anti-crosstalk capability of the system, but more importantly, it effectively overcomes the adverse effect of the detector's dead time on the ranging performance. The experiment results show that the ranging performance of the true random coded method is obviously better than that of the pseudo-random coded method. As a result, a three-dimensional scanning imaging of a model car is completed by the true random coded method.

Keywords: Lidar; photon counting; true random coded; pseudo-random coded

Introduction

Photon counting Lidar has become more and more popular in the ranging and three-dimensional imaging area due to its capability of extremely weak signal detection [1–4]. But it's a statistical sampling technique and needs to accumulate enough photons to establish statistical histograms. However, the multi-period cumulative process greatly slows down the measuring speed and it is not appropriate for scenarios that require quick measurements. In order to solve this problem, researchers have proposed the pseudo-random coded photon counting Lidars.

The combination of pseudo-random coded method and photon counting ranging technique is called the pseudo-random coded photon counting ranging Lidar. The pseudo-random coded photon counting ranging Lidar has been favored by more and more researchers due to its advantages of low transmitting power, overcoming range ambiguity and fast detection. In 1983, Takeuchi et al. took a random phase code modulate continuous-wave laser with an external optical modulator, as a laser source in a laser ranging system to improve the signal-to-noise ratio[5]. Sun[6] applied pseudo-random coded method to photon counting laser altimeter for long-range targets

ranging. Hiskett[7], Krichel[8] and Ullrich[9] used a finite non-periodic pulse train or pulse-position modulation technique to resolve range ambiguity. Zhang realized the detection of a non-cooperative target in 1.2 km using the pseudo-random coded photon counting Lidar ranging technique[10]. Yang realized high spatial resolution detection using a high speed pseudo-random modulation photon counting fiber laser ranging system[11]. In addition, it can effectively improve the measurement speed of the system compared with the pulse accumulation photon counting Lidar[12–13].

However, the pseudo-random coded photon counting Lidar also has some shortcomings. Firstly, this method usually uses mature M-sequence or other random sequence. In both cases, the interval between two adjacent '1' bits is less than the single photon detector's dead time. When the single photon detector responds to a photon, it will enter the dead period and cannot respond to any other arriving photons during it. Thus, if the pulse interval of two adjacent '1' bits is less than the single photon detector's dead time, the front '1' bit will make the single photon detector dead, and the latter '1' bit cannot be responded even the signal photons arrived. Therefore, the ranging performance is degraded. To overcome this issue,

[1]Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China; [2]University of Chinese Academy of Sciences, Beijing 100049, China; [3]Key Laboratory of Science and Technology on Space Optoelectronic Precision Measurement, Chinese Academy of Sciences, Chengdu 610209, China.
*Correspondence: B Liu, E-mail: boliu@ioe.ac.cn

we propose the true random coded method. It's well known that the noise pulse of a single photon detector is completely random, thus we take advantage of this character, and use the noise pulse as the signal source to drive the laser and generate a true random laser pulse sequence for the Lidar detection. The true random coded method has two advantages over the pseudo-random coded method.

Firstly, a single photon detector will not generate any pulse during its dead time, which means that the output pulse interval between any two adjacent pulses is larger than its dead time. Therefore, we can consider that any two '1' bits in the true random sequence are independent of each other. In other words, they do not have a negative effect on each other. In this case, the dead time effect can be completely avoided.

Secondly, due to its physical randomness, the probability of that two true random sequences are identical is extremely low, thus it has excellent anti-crosstalk performance. Therefore, the true random coded photon counting Lidar has obvious advantages in the scenario where multiple Lidars are working simultaneously, such as vehicle automatic driving[14].

Figure 1 is a schematic for a pseudo-random sequence (a) and a true random sequence (b). The pseudo-random sequence seems random, however it is produced by mathematical methods with certain rules, which is pro-
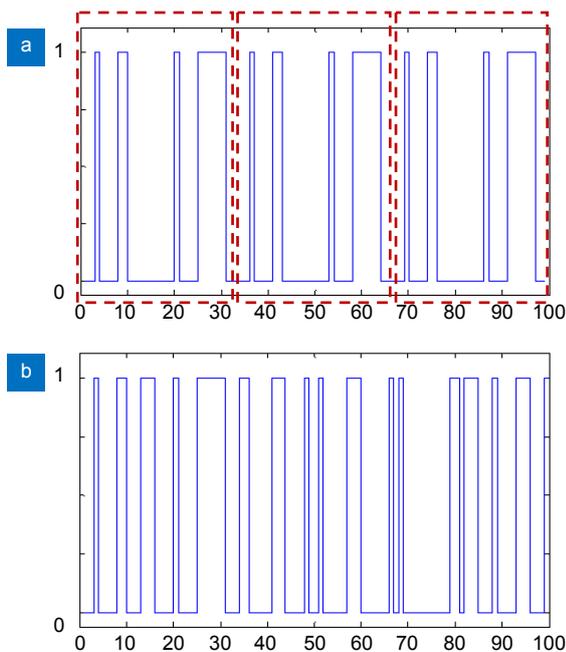
duced determinately and repeated periodically. The true random sequence is never repeated and ever-changing.

In addition, it is worth mentioning that for the single photon detector used to generate random pulses, we don't need it has high performance as the one used for return signal detecting, because it can be much cheaper than a function generator. Furthermore, one can even think about utilizing the noise from the receiving detector itself (Gm-APD 2 in Fig.2) for the true random sequence generation. We are currently working on this part.

System description

System structure and ranging principle

As shown in Fig. 2, the system uses two single photon detectors labeled Gm-APD 1 and Gm-APD 2, respectively. Gm-APD 1 is used as the true random signal generator, and Gm-APD 2 is used as the detector. The Gm-APD 1 outputs a random electric pulse sequence. The high voltage of the random electric pulse sequence is recorded as the '1' bit. The output electric pulse width of common single photon detectors is generally 10-20 ns. We add a pulse shaping circuit to narrow the electric pulse width of the Gm-APD 1 to 4 ns. The shaped random sequence is recorded by the channel 1 (Ch1) of the TCSPC (time-correlated single photon counting) module, which serves as a reference sequence for correlation operation and is recorded as $a(n)$. The laser is modulated internally or externally to obtain the true random optical pulse sequence for targets detection. The echo signal received by the optical system is detected by the Gm-APD 2, and the output signal of the Gm-APD 2 is stored by the channel 2 (Ch2) of the TCSPC module and is recorded as $b(n)$. The

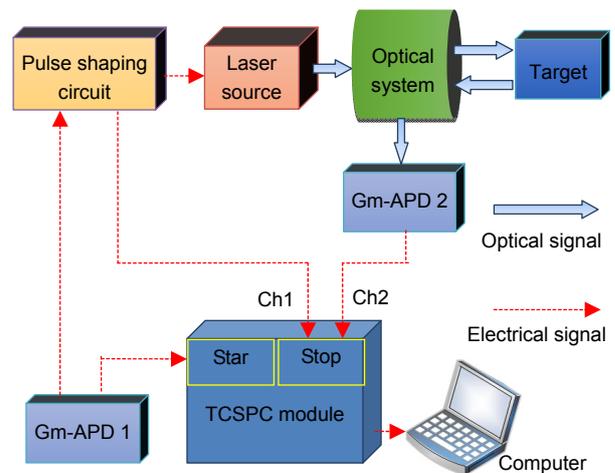Fig.1 | (a) Pseudo-random sequence and (b) true random sequence.

Fig. 2 | True random coded photon counting Lidar system.

reference sequence $a(n)$ and echo sequence $b(n)$ are correlated. The peak position of cross-correlation function $g(\tau)$ is the ToF (Time of Flight) of the true random optical pulse sequence.

$$g(\tau) = \sum_{n=1}^{N} a(n)\,b(n) = \begin{cases} \dfrac{N+1}{2}, & \tau = \pm\dfrac{2R}{c}, \pm 2\cdot\dfrac{2R}{c}, \cdots \\ \approx 0, & \tau \neq \pm\dfrac{2R}{c}, \pm 2\cdot\dfrac{2R}{c}, \cdots \end{cases}, (1)$$

where N is the number of '1' bit in the true random sequence, R is the target distance, and c is the speed of light. When τ corresponds to the time of flight, the cross-correlation function $g(\tau)$ has the maximum value.
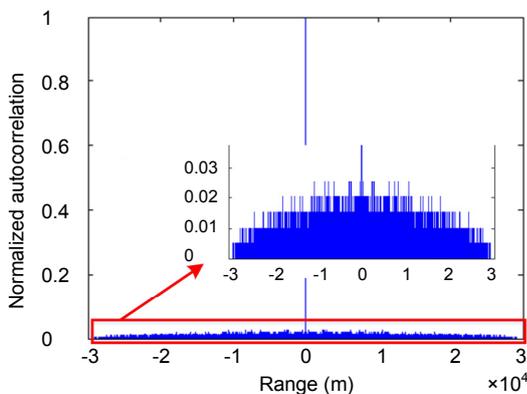
The auto-correlation of the true random coded photon counting Lidar

In order to prove the feasibility of the true random coded photon counting ranging Lidar, we first need to verify the auto-correlation of true random sequences. This is the premise that the true random coded photon counting Lidar system can be used for ranging. The number of '1' bits per unit time is called the mean pulse count density. The normalized auto-correlation coefficient of the random sequence can be written as

$$\rho(\tau) = \frac{1}{T}\int_0^T a(t)\,a(t-\tau)\mathrm{d}t \quad, \qquad (2)$$

where $a(t)$ is the true random sequence and T is the period of the true random sequence (the length of the true random sequence).

We record a 200 μs length true random sequence and complete auto-correlation operation. As shown in Fig. 3, the true random sequence has good auto-correlation. The side-lobes of the auto-correlation function are in the red box. After zoom-in, we can see that the maximum value of the side-lobes is less than 0.03 in the normalized auto-correlation function. Thus, it is feasible to use the true

Fig. 3 | Normalized auto-correlation function of the true random sequence

random coded photon counting Lidar for target ranging.

In this section, the feasibility of the true random coded photon counting Lidar was proved. And in the following section, we mainly show the ranging performance improvement of the true random coded photon counting Lidar compared with the traditional pseudo-random coded photon counting Lidar.

Experiment

Ranging performance comparison

We built an experimental platform, with which the ranging performances of the true random coded method and the pseudo-random coded method are compared. In the true random coded method, the density of '1' bit is 1 Mcps, and the length of the true random sequence is 200 μs. In other words, about 200 laser pulses are emitted in a true random sequence. For the pseudo-random coded method, we choose the commonly used M sequence. To generate a common M sequence with the same length (200 μs) and the same pulse width (4 ns), the degree of the M sequence will be 14. The main parameters of the two Lidar systems are given in Table 1.

Table 1 | Main parameters of the Lidar system.

Parameter	Value
Dead time	35 ns
Pulse width	4 ns
Noise count	1 Mcps
Photon detection efficiency	2%
Time resolution of TCSPC module	64 ps

When the noise count is 1 Mcps, we compare the auto-correlation function of the true random coded method and the pseudo-random coded method under different echo signal intensities. As shown in Fig. 4, the first column is the auto-correlation functions of the true random coded method, and the second column is the pseudo-random coded method. Figures 4(a) and 4(b) show the auto-correlation functions of the two methods when the mean echo signal photon numbers of per '1' bit are 1 and 3, respectively. The detection efficiency of the Gm-APD 2 is about 2%. When the average number of echo photons of a '1' bit is 1, its average detection probability is about 2%.

For the same echo signal intensity, the side-lobe of the true random coded method is lower than that of the pseudo-random coded method, which means that the ranging performance of the true random coded method
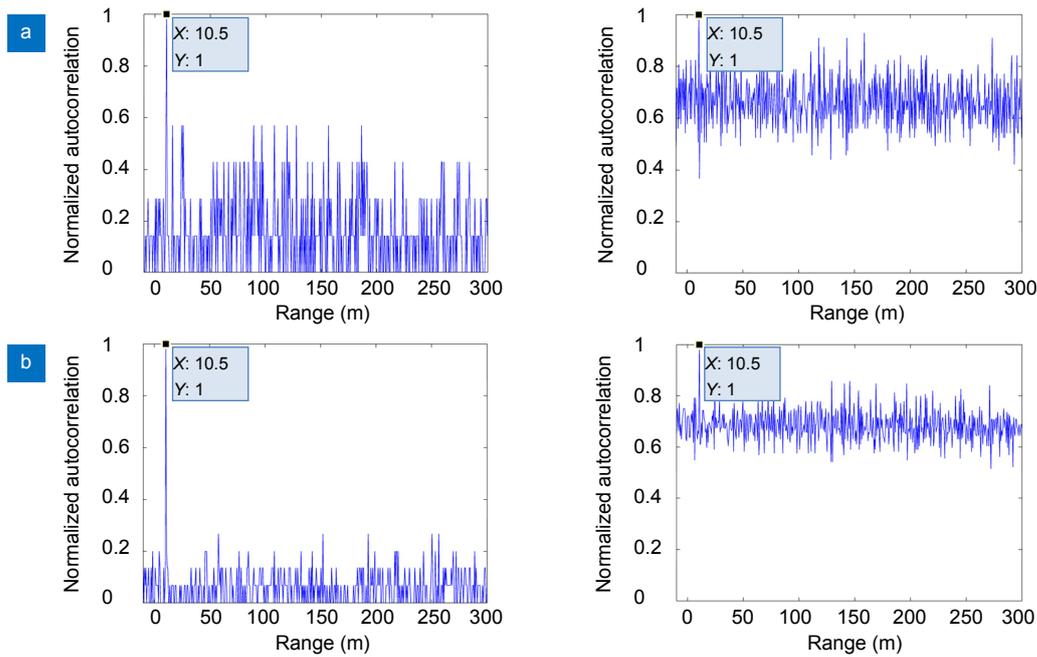
Fig. 4 | Normalized auto-correlation range images with two different echo photons number for the true random coded method and the pseudo-random coded method.

is better than that of the pseudo-random coded method. Further, the auto-correlation function's side-lobes of the two methods decrease with the enhancement of echo signal intensity, but the true random coded method has obvious advantages over the pseudo-random coded method in suppressing side-lobes.

The comparisons above are between true random sequences and common M sequences with the same length and the same pulse width. When the M sequence is modified sparsely enough that with the same pulse numbers as the true random sequence by adding '0' codes, it seems the same as the true random sequence if we only look at just one period. However, the sparse pseudo-random sequence is repeated periodically (as shown in Fig. 1), which will cause serious crosstalk. It is analyzed in the next subsection.

Meanwhile, the probability that the system can correctly identify targets is also an important index to evaluate the ranging performance. When the noise counts are 1 Mcps and the mean echo photons number per '1' bit is 1–5, 300 experiments are completed with different echo signal intensity for the two methods, respectively. Under different echo signal intensities, the probabilities of the two methods correctly measuring the target distance are shown in Fig. 5.

Figure 5 shows the change trend of target detection probabilities of both methods with different mean echo photons numbers. It can be found that with the increase

of the mean echo photons number, the detection probability increases gradually and tends to be saturated for both methods.
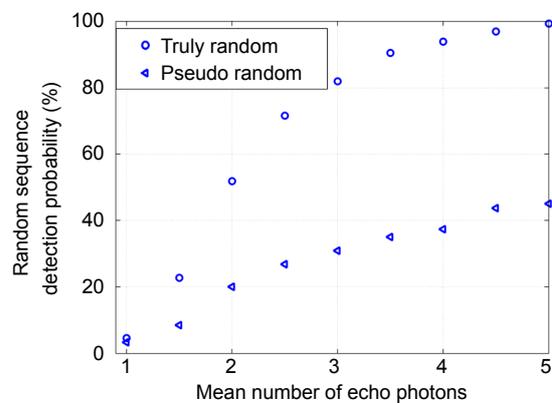
Fig. 5 | The detection probability statistical results of the true random coded method and the pseudo-random coded method at different mean echo photons number.

When the echo signal intensity is weak, the detection probability of both methods is relatively low. And the difference of detection probabilities between the two methods is not obvious. This is because when the number of echo photons is small, the detection probability of the '1' bit in the two methods is low. There are many '1' bits in the true random sequence and the pseudo-random sequence that cannot be detected, which makes the correlation of both methods poor. Meanwhile, when the number of echo photons is small, the influence of dead time on

the pseudo-random coded method is not obvious. Thus, the detection probability of both methods is relatively low, but there is no obvious difference.

With the increase of echo signal intensity, the detection probability of '1' bit increases. The true random coded method can effectively avoid the influence of detector dead time. Thus, the detection probability increases rapidly, and finally approaches 100%. However, with the increase of echo signal intensity, the influence of dead time on the pseudo-random coded method is more obvious. That is to say, there are more '1' bits in the pseudo-random coded method which cannot be detected because the detector enters the dead period. Therefore, the detection probability of the pseudo-random coded increases slowly, and is significantly lower than that of the true random coded method.

Anti-crosstalk performance comparison

To evaluate the anti-crosstalk performance of the coding, we use the cross-correlation function. The normalized cross-correlation can be written as:

$$\rho_c(\tau) = \frac{1}{T}\int_0^T a_1(t)\, a_2(t-\tau)\mathrm{d}t \;, \qquad (3)$$

where a_1 and a_2 are two different sequences and T is the period of them (the length of the sequences). We use the same true random sequence as above. For the M sequence, it is modified by adding '0' codes to make it sparse enough as same as the true random one (200 pulses in 200 μs).

The normalized cross-correlation for the true random sequence (a) and the sparse pseudo-random sequence (b) are shown in Fig. 6. It can be seen that the cross-correlation for the true random sequence is bad, which means that one true random sequence can only get good correlation with itself and have bad correlation with other sequences, in another word, it has good anti-crosstalk performance. For the sparse pseudo-random sequence, it still has good correlation with other sequences, which means that it cannot distinguish itself from others, in another word, it has bad anti-crosstalk performance.

Scanning imaging of the true random coded method

From Fig. 4 and Fig. 5, it can be found that the ranging performance of the true random coded photon counting Lidar is obviously improved compared with the traditional pseudo random coded method. To demonstrate the imaging capability of the true random coded photon counting Lidar, the optics system is placed on a two-dimensional turntable. As shown in Fig. 7, the three-
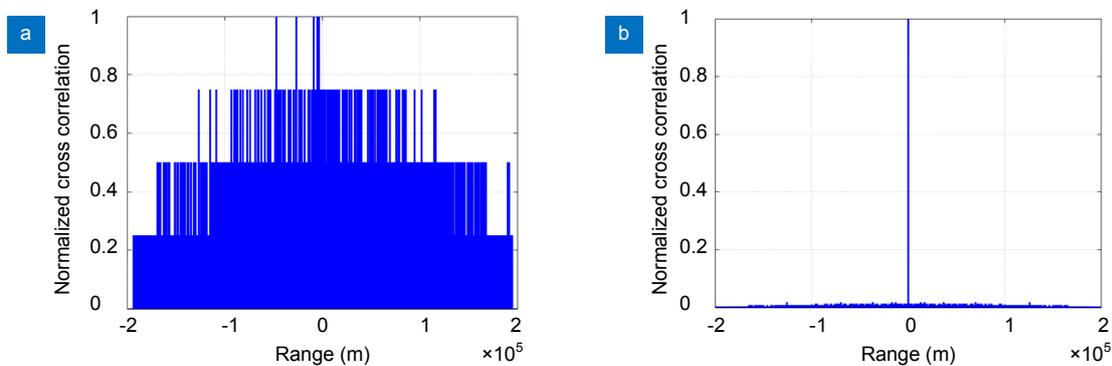

Fig. 6 | Normalized cross-correlation range images for the true random sequence (a) and the sparse pseudo-random sequence (b).
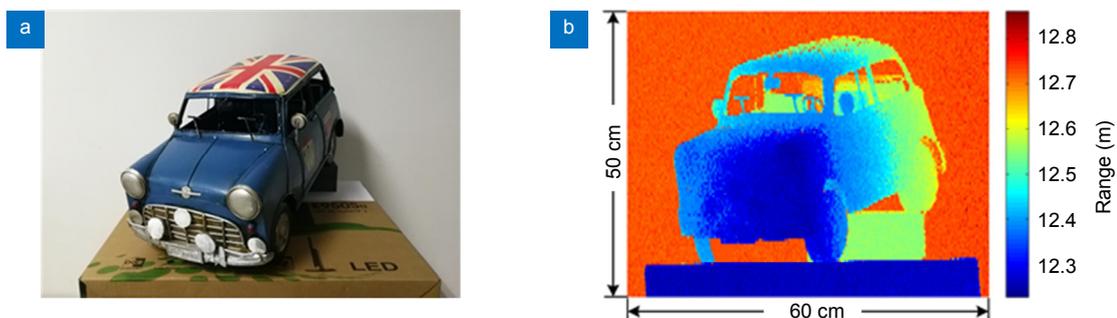

Fig. 7 | (a) The picture of the model car and (b) three-dimensional scanning imaging of the model car.

dimensional scanning imaging of the model car was completed. Figure 7(a) is the picture of the model car, and Fig. 7(b) is the three-dimensional scanning image obtained by the true random coded method. Some details of the model car, such as rearview mirrors, wipers, steering wheel, etc., are clearly imaged. The key parameters for the depth profile measurement are summarized in Table 2.

Table 2 | Key parameters for the depth profile measurement.

Parameter	Value
Power	30 μW
Pixel dwell time	200 μs
Pulse repetition frequency	5 kHz
Scan dimensions (width × height)	0.6 m × 0.5 m
Resolution of scanned image (pixels)	300 × 250

Conclusion

The true random coded photon counting Lidar system retains the advantages of traditional pseudo random coded photon counting Lidar system, such as low transmitting power, fast detection and overcoming range ambiguity. It uses a single photon detector as a random sequence generator. Single photon detector generates random sequence, which belongs to true random sequence and has very high anti-crosstalk ability. More importantly, it can effectively avoid the influence of detector's dead time and improve the detection performance of the system. A simple experimental platform is built to complete the principle verification. Experiments verify that the ranging performance of the true random coded method is obviously better than that of the traditional pseudo-random coded method. Finally, we use the true random coded photon counting Lidar to complete a three-dimensional scanning imaging of a model car.

References

1. McCarthy A, Collins R J, Krichel N J, Fernández V, Wallace A M et al. Long-range time-of-flight scanning sensor based on high-speed time-correlated single-photon counting. *Appl Opt* **48**, 6241–6251 (2009).
2. Albota M A, Heinrichs R M, Kocher D G, Marino R M, Fouche D G et al. Three-dimensional imaging laser radar with a photon-counting avalanche photodiode array and microchip laser. *Appl Opt* **41**, 7671–7678 (2002).
3. Degnan J, Wells D, Machan R, Leventhal E. Second generation airborne 3D imaging lidars based on photon counting. *Proc SPIE* **6771**, 67710N (2007).
4. Degnan J J. Scanning, multibeam, single photon lidars for rapid, large scale, high resolution, topographic and bathymetric mapping. *Remote Sens* **8**, 958 (2016).
5. Takeuchi N, Sugimoto N, Baba H, Sakurai K. Random modulation CW lidar. *Appl Opt* **22**, 1382–1386 (1983).
6. Sun X L, Abshire J B, Krainak M A, Hasselbrack W B. Photon counting pseudorandom noise code laser altimeters. *Proc SPIE* **6771**, 677100 (2007).
7. Hiskett P A, Parry C S, McCarthy A, Buller G S. A photon-counting time-of-flight ranging technique developed for the avoidance of range ambiguity at gigahertz clock rates. *Opt Express* **16**, 13685–13698 (2008).
8. Krichel N J, McCarthy A, Buller G S. Resolving range ambiguity in a photon counting depth imager operating at kilometer distances. *Opt Express* **18**, 9192–9206 (2010).
9. Rieger P, Ullrich A. A novel range ambiguity resolution technique applying pulse-position modulation in time-of-flight ranging applications. *Proc SPIE* **8379**, 83790R (2012).
10. Zhang Y F, He Y, Yang F, Luo Y, Chen W B. Three-dimensional imaging Lidar system based on high speed pseudorandom modulation and photon counting. *Chin Opt Lett* **14**, 111101 (2016).
11. Yang F, Zhang X, He Y, Chen W B. High speed pseudorandom Modulation fiber laser ranging system. *Chin Opt Lett* **12**, 082801 (2014).
12. Zhang Q, Soon H W, Tian H T, Fernando S, Ha Y J et al. Pseudo-random single photon counting for time-resolved optical measurement. *Opt Express* **16**, 13233–13239 (2008).
13. Zhang Q, Chen L, Chen N G. Pseudo-random single photon counting: a high-speed implementation. *Biomed Opt Express* **1**, 41–46 (2010).
14. Zhang F, Du P F, Liu Q, Gong M L, Fu X. Adaptive strategy for CPPM single-photon collision avoidance LIDAR against dynamic crosstalk. *Opt Express* **25**, 12237–12250 (2017).

Acknowledgements

Competing interests

The authors declare no competing financial interests.